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Experimental sensitivity on searching for CP violation at BES-III*

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The CP violation in the D system is predicted to be an unobserved level in the Standard Model. In this paper, we describe the method of searching for CP violation decay processes with the coherently produced $D^0\bar{D}^0$ mesons from the $\psi(3770)$ decay. The CP violation decay processes can be searched for at the BES-III experiment. The experimental sensitivity for searching for the CP violation can reach about a 10^{-4} level with a $\psi(3770)$ data sample of about 20 fb^{-1}.

Keywords: CP violation, charm meson, BES-III
PACC: 1130E, 2900

1. Introduction

Since the discovery of CP violation in the decays of neutral kaon in 1964,[1] many observations show that CP violation has been established in both K and B systems, and these observations are consistent with the prediction of the Standard Model (SM). In the D system, the CP violation effect is expected to be highly suppressed in the SM. Therefore, searching for observable CP violation effect in the D system can serve as a test for the SM and a probe for new physics. In the past fifteen years, many efforts were carried out through the measurements of CP asymmetries in various D decay modes and through the measurements of CP lifetime asymmetries of D^0 meson, but unfortunately, all of these observations suffer from large uncertainties and cannot draw a decisive conclusion.

In D meson decays, there exist four types of CP violating signals and corresponding study methods.

1) CP violation in D^0–$\bar{D}^0$ mixing. The mixing induced CP asymmetry can be best isolated in the semileptonic decays of D^0 meson.[2] This asymmetry represents the difference between the rates for $\bar{D}^0 \to D^0 \to l^+X$ and $D^0 \to \bar{D}^0 \to l^-X$. If the phases in the $\bar{D}^0 \to D^0$ and the $D^0 \to \bar{D}^0$ transition amplitudes differ from each other, a non-vanishing CP violation happens.
2) CP violation in direct decay. This asymmetry occurs when the absolute values of the decay amplitude to a final state for the D and $\bar{D}$ mesons are different. And in the case of the charged D meson decays, where mixing effects are absent, this is the only possible observable CP asymmetry.
3) CP violation in the interference of decay with and without mixing. This asymmetry can be measured with any final states decayed from $D^0/\bar{D}^0$ mesons.
4) CP violation in the CP-forbidden decay. At the $\psi(3770)$, for the CP eigenvalue of $\psi(3770)$ is even and the $D^0\bar{D}^0$ mesons are produced coherently, if both the D^0 and the $\bar{D}^0$ decay into CP eigenstates, the decays $\psi(3770) \to f^a_{CP=+}f^b_{CP=+}$ or $f^a_{CP=-}f^b_{CP=-}$ are CP forbidden, where $f^{a,b}_{CP=+(-)}$ denotes a CP even (odd) eigenstate. Thus the observation of such final states constitutes evidence of the CP violation.

The last method makes the best use of the advantage of the BES-III $\psi(3770)$ data, collected just above the $D\bar{D}$ production threshold which provide the cleanest signal events, and avoids the large uncertainties existing in all of the measurements based on the non-coherently produced D meson decays. In this paper, we describe the method and set the experimental sensitivity of searching for CP violation with the coherently produced $D^0\bar{D}^0$ mesons at the $\psi(3770)$ at the BES-III by Monte Carlo simulation.

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2. BES-III detector

The BES-III detector[3] is a large solid-angle magnetic spectrometer which is working at the BEPC-II collider. It consists of a berylium beam pipe, a small cell main drift chamber (MDC) filled with a helium-based gas, time-of-flight (TOF) counters for particle identification made of plastic scintillators, an electromagnetic calorimeter (EMC) made of CsI (Tl) crystals, a superconducting solenoidal magnet with a field of 1 T, and a muon identification system using the magnet yoke interleaved with the resistive plate counters (RPC). The BEPC-II collider is designed to work at the τ-charm energy region with a peak luminosity of 10^{33} cm$^{-2}\cdot$s^{-1} at $\psi(3770)$. As a conservative estimation, a data sample with an integrated luminosity of about 5 fb^{-1} will be collected during one year's running. This will be the largest $\psi(3770)$ data sample in the world. With the high luminosity, many important measurements on charm decays can be performed at the BES-III.

3. Monte Carlo sample

The Monte Carlo (MC) events used in the analysis are generated as $e^+e^-\to\psi(3770)\to D\bar{D}$ at $\sqrt{s}=$ 3.773 GeV where the $D\bar{D}$ mesons are set to decay into the assigned final states with the branching fractions quoted from PDG.[4] The particle trajectories are simulated with the GEANT4[5] based Monte Carlo simulation package for the BES-III detector.[6] The Monte Carlo events are generated and reconstructed with the BES-III offline software system (BOSS).[7]

With the BES-III detector, we are going to collect 20 fb^{-1} of $\psi(3770)$ data for ~ 4 years' running at the $\psi(3770)$ peak. With this data sample, more than 1.36×10^6 CP even tag and 5.10×10^6 CP odd tag events are produced:

$$CP=+:\pi^+\pi^-,\ \ K^+K^-,\ \ \pi^0\pi^0,\ \ \rho^0\pi^0,\ \ K^0_sK^0_s,\ \ldots$$
$$CP=-:K^0_s\pi^0,\ \ K^0_s\rho^0,\ \ K^0_s\phi,\ \ K^0_s\omega,\ \ K^0_s\eta,\ \ldots.$$

As a conservative estimation, considering the detection efficiency of each tag mode, about 4.3×10^5 CP even tag events and about 7.8×10^5 CP odd tag events can be accumulated.

In this analysis, we make use of the CP eigenstates K^+K^- and $\pi^+\pi^-$ in the tagging and recoiling sides, i.e., two double tag modes (f^a vs. f^b) K^+K^- vs. K^+K^- and $\pi^+\pi^-$ vs. K^+K^-, to probe for the CP violation decay processes. And one can find the main background comes from K^+K^- vs. $K^-\pi^+$, $\pi^+\pi^-$ vs. $K^-\pi^+$, $K^+\pi^-$ vs. $K^-\pi^+$ in each double tag mode.

We generate the special Monte Carlo samples according to the expected numbers of signal and background channels in a 20 fb^{-1} $\psi(3770)$ data sample, which are shown in Table 1. Based on these MC samples, we can estimate the experimental sensitivity.

Table 1. Expected numbers of events in a 20 fb^{-1} $\psi(3770)$ data sample, where $N_{D^0\bar{D}^0}=7.1\times10^7$, $\mathcal{B}(K^+K^-)$, $\mathcal{B}(\pi^+\pi^-)$, and $\mathcal{B}(K^-\pi^+)$ are the branching fractions of $D^0\to K^+K^-$, $D^0\to\pi^+\pi^-$ and $D^0\to K^-\pi^+$ quoted from PDG.[4]

style	decay mode	expected number of event
signal	$\bar{D}^0\to K^+K^-/D^0\to K^+K^-$	$N_{D^0\bar{D}^0}\cdot\mathcal{B}^2(K^+K^-)=1050$
signal	$\bar{D}^0\to\pi^+\pi^-/D^0\to K^+K^-$	$2\cdot N_{D^0\bar{D}^0}\cdot\mathcal{B}(\pi^+\pi^-)\cdot\mathcal{B}(K^+K^-)=746$
background	$\bar{D}^0\to K^+K^-/D^0\to K^-\pi^+$	$2\cdot N_{D^0\bar{D}^0}\cdot\mathcal{B}(K^+K^-)\cdot\mathcal{B}(K^-\pi^+)=20786$
background	$\bar{D}^0\to\pi^+\pi^-/D^0\to K^-\pi^+$	$2\cdot N_{D^0\bar{D}^0}\cdot\mathcal{B}(\pi^+\pi^-)\cdot\mathcal{B}(K^-\pi^+)=7383$
background	$\bar{D}^0\to K^+\pi^-/D^0\to K^-\pi^+$	$N_{D^0\bar{D}^0}\cdot\mathcal{B}^2(K^-\pi^+)=102847$

4. Analysis

4.1. Event selection

To select the candidate events, we require the number of charged tracks to be four with a total charge of zero. All charged tracks should be well reconstructed in the MDC with good helix fits and satisfy $|\cos\theta|<0.93$, where θ is the polar angle of the track. Each track must originate from the interaction point in three dimensions, which is defined by $V_{xy}<1.0$ cm and $|V_z|<5.0$ cm, where V_{xy} and $|V_z|$ are the closest approach of the charged track in the xy-plane and z direction.

Charged pions and kaons are identified by means of the dE/dx (ionization energy loss) and TOF (time of flight) measurements. Pion identification requires

consistency with the pion hypothesis at a confidence level (CL_π) greater than 0.1%. In order to reduce the misidentification, a kaon candidate is required to have a confidence level (CL_K) for a kaon hypothesis greater than that for a pion hypothesis.

The K^+K^- vs. K^+K^- and $\pi^+\pi^-$ vs. K^+K^- modes are selected by reconstructing $\bar{D}^0$ ($\bar{D}^0 \to K^+K^-/\pi^+\pi^-$) mesons as tagged events and searching for the coherent D^0 ($D^0 \to K^+K^-$) in the recoiling side. We identify D^0 candidates by their momentum and total energies. Two variables reflecting energy and momentum conservation are used. We define the energy difference $\Delta E \equiv E_{D^0} - E_{\rm b}$, where E_{D^0} is the total measured energy of the D^0 candidate daughter particles and $E_{\rm b}$ is the energy of the $e^\pm$ beam. Candidates are rejected if they fail the selection cut of $|\Delta E| < 3 \times \sigma_{\Delta E}$, which are tailored for each individual decay channel, and $\sigma_{\Delta E}$ is the standard deviation of the ΔE distribution. We calculate a beam-constrained mass $M^2_{\rm BC} \equiv E^2_{\rm b} - p^2_{D^0}$ of the D^0 candidate, where p_{D^0} is the D^0 candidate momentum. If there is more than one candidate in a particular D^0 decay mode satisfying the above selection criteria, we accept the one with the smallest $|\Delta E|$.

4.2. Data yields

Valid D^0 candidates produce a peak in the $M_{\rm BC}$ spectrum at the D^0 mass. For the tagged $\bar{D}^0$ signal in the $M_{\rm BC}$ distribution is very clean, we neglect the background from the sideband region of tagged spectra. Figure 1 shows the D^0 beam-constraint mass spectra of the two double tag modes, a fit to the spectra with a Gaussian function for the D^0 signal and an ARGUS function[8] to describe the background shape yields the number of observed events ($N^{100\%}_{\rm CPV}$) for each of the two modes, under the assumption that the CP is totally violated, which are summarized in Table 2.

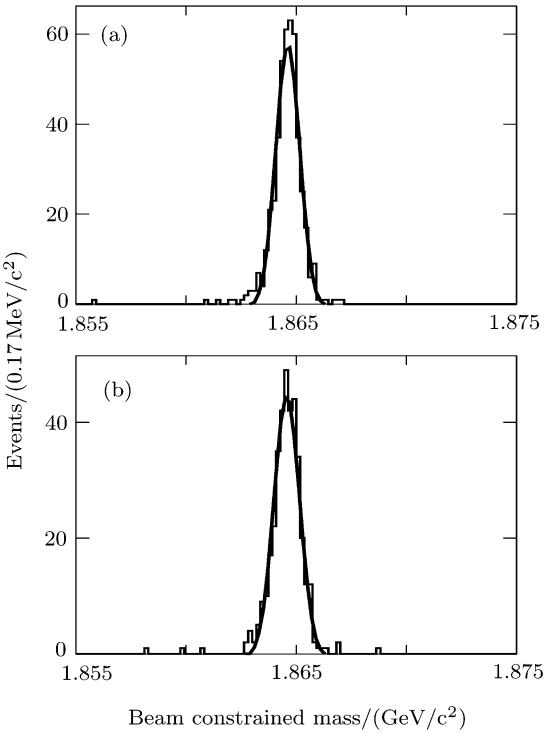


Fig.1. The fitted distributions of D^0 beam-constraint mass for the two double tag modes: (a) for $\bar{D}^0 \to K^+K^-$ vs. $D^0 \to K^+K^-$; (b) for $\bar{D}^0 \to \pi^+\pi^-$ vs. $D^0 \to K^+K^-$.

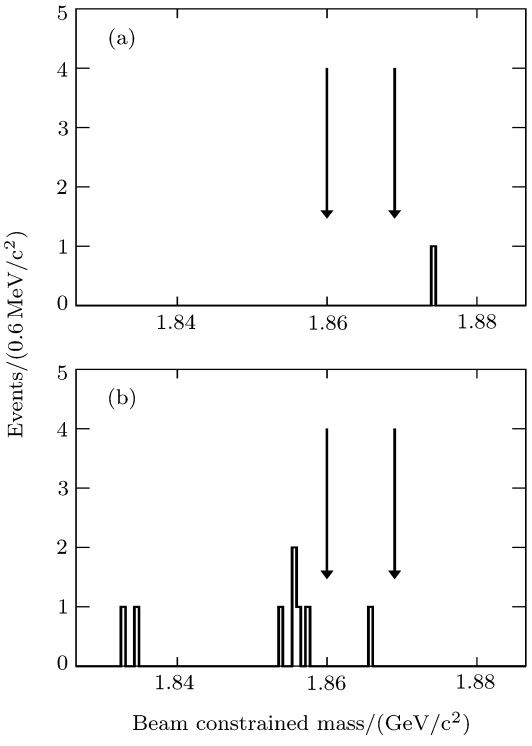


Fig.2. The D^0 beam-constraint mass distributions from the three main background channels for each of the two double tag modes: (a) for $\bar{D}^0 \to K^+K^-$ vs. $D^0 \to K^+K^-$ mode, (b) for $\bar{D}^0 \to \pi^+\pi^-$ vs. $D^0 \to K^+K^-$ mode. The arrows indicate the cut $|M_{\rm BC} - M_{D^0}| < 3 \times \sigma_{M_{\rm BC}}$.

To obtain the yields from the main background channels for the two modes, we count the resulting $M_{\rm BC}$ distribution for the events within $|M_{\rm BC} - M_{D^0}| < 3 \times \sigma_{M_{\rm BC}}$, where $\sigma_{M_{\rm BC}}$ is the mass resolution of the $M_{\rm BC}$ distribution. Figure 2 shows the resulting $M_{\rm BC}$ distributions for each double tag mode of the three main background channels, after applying the above event selection criteria. Only one contaminated background

event is observed from the background channel $\bar{D}^0 \to K^-\pi^+/D^0 \to K^+\pi^-$ in the double tag mode $\bar{D}^0 \to \pi^+\pi^-/D^0 \to K^+K^-$. The yielding numbers ($N^{\rm bg}_{\rm CPV}$) of events are summarized in Table 2.

Table 2. Results for the CP violation experimental sensitivity.

signal mode	$N^{100\%}_{\rm CPV}$	background mode	$N^{\rm bg}_{\rm CPV}$
$\bar{D}^0 \to K^+K^-$ vs. $D^0 \to K^+K^-$	443	$D^0 \to K^+K^-/\bar{D}^0 \to K^-\pi^+$ $D^0 \to \pi^+\pi^-/\bar{D}^0 \to K^-\pi^+$ $D^0 \to K^-\pi^+/\bar{D}^0 \to K^+\pi^-$	0
$\bar{D}^0 \to \pi^+\pi^-$ vs. $D^0 \to K^+K^-$	370	$D^0 \to K^+K^-/\bar{D}^0 \to K^-\pi^+$ $D^0 \to \pi^+\pi^-/\bar{D}^0 \to K^-\pi^+$ $D^0 \to K^-\pi^+/\bar{D}^0 \to K^+\pi^-$	1

4.3. Result

The CP asymmetry ($\mathcal{A}_{CP}$) can be calculated by

$$\mathcal{A}_{CP} = N_{\rm CPV}/N^{100\%}_{\rm CPV}, \quad (1)$$

where $N^{100\%}_{\rm CPV}$ is the number of events in the case of assuming that the CP is totally violated, and $N_{\rm CPV} = N^{\rm obs}_{\rm CPV} - N^{\rm bg}_{\rm CPV}$ is the number of events for the CP violation process, where $N^{\rm obs}_{\rm CPV}$ is the observed number of CP violation events and $N^{\rm bg}_{\rm CPV}$ is the number of background events survived.

For the estimation of the experimental sensitivity by Monte Carlo simulation, $N^{\rm obs}_{\rm CPV}$ is zero. $N^{\rm bg}_{\rm CPV}$ can be obtained by analyzing the Monte Carlo samples described in Section 3. Taking the number of $\bar{D}^0$ reconstructed by K^+K^- and $\pi^+\pi^-$ as the tagging meson and searching for the CP forbidden decay K^+K^- in the recoiling side, we estimate the experimental sensitivity to be 3×10^{-3} at 90% confidence level. With the coming BES-III $\psi(3770)$ data, we can employ all the CP eigenstate final states to reconstruct the tagged D meson, thus the experimental sensitivity can reach about a 10^{-4} level.

5. Summary

In summary, we report the search for CP violation decay processes with the coherently produced $D^0\bar{D}^0$ mesons at $\psi(3770)$ at the BES-III based on Monte Carlo simulation. The expected experimental sensitivity can reach about a 10^{-4} level with 20 fb^{-1} of $\psi(3770)$ data. CP violation at the percent level has never been observed in any experiments in the D meson system.[9] But signals of 10^{-3} level are expected in some neutral D meson decays within the SM,[10] although such theoretical estimates involve large uncertainties. If a CP asymmetry of percent level is observed at the BES-III, it will clearly signify the existence of new physics in the charm sector. To uncover the details about CP violation in charm decays, we expect that the BES-III/BEPC-II will play an important role.

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